Title: AI for Extreme Volcanic Climate Forcing and Feedback Forecasting in
                the 21st century

Author(s):   Dubey, Manvendra Krishna
                Benedict, James Joseph
                O'Malley, Daniel
                Nadiga, Balasubramanya T.
                Johnson, Paul Allan
                Viswanathan, Hari S.
                Chylek, Petr
                Carns, Simon

Intended for: BER EESS AI Climate White Paper for LANL

Issued: 2021-02-16

AI for Extreme Volcanic Climate Forcing and Feedback Forecasting in the 21st century

M. Dubey*, J. Benedict, D. O'Malley, B. Nadiga, P. Johnson, H. Viswanathan, P. Chylek & S. Cairns

Focal Areas: Our paradigm-shifting framework will apply machine learning and perform physical analysis of contemporary volcanoes to develop sound forecasts of extreme eruptions in the 21st century and their abrupt drying and cooling impacts on the warming climate. We will also bridge climate data driven regression models and earth system model output to trace teleconnections that exacerbate regional impacts such as Arctic amplification and western US droughts.

The Science Challenge: Despite extreme and abrupt impacts of volcanoes that cool the globe by 0.5-3 °C for months to years over the past 2 centuries (Tambura, Krakatoa, Mt. Pinatubo) and by 5°C 73,000 years ago (Mt. Toba, 100-1000 times faster than GHG warming rates) they are ignored in IPCC future climate assessments. Extensive characterization of Pinatubo's climate effects shows complex regional impacts via teleconnections and couplings to natural modes by two way stratosphere-troposphere wave interactions.[1a,b] We are poised to capturing volcanic effects in 21st IPCC climate scenarios and fill a fundamental gap in predicting how couplings between human and natural forcing will affect future climate.

Rationale: Our planet has experienced 2 massive, low-latitude volcanoes in each of the 19th and 20th centuries that injected huge amounts of sulfur dioxide (SO_2) into the stratosphere. The enhanced sulfate aerosol layer reflected more sunlight to cause global shading, cooling and drying for several years and thus altering weather, vegetation and food production. These global climate effects are very well documented and exceeded those from natural internal variability. Anticipating and predicting the effects of extreme volcanic activity in the 21st century remains an unaddressed grand challenge. Combining machine learning methods with physical and probabilistic analysis provides a route for filling this gap, by building on the characteristics of past eruptions and their impacts on climate. Overarching questions that our white paper will answer include:

1. What is the probable extreme volcanic forcing in the 21st century?
2. What are the climate effects of this forcing for increasing GHG scenarios?
3. What are the water cycle impacts in sensitive and vulnerable regions such as the Arctic and western US?
4. How will future volcanic cooling and drying interact with growing GHG forcing and internal variability of our climate system?

Forecast Future Volcanoes: In order to forecast volcanoes, we will exploit machine learning methods using extensive records of past eruptions including their latitude, longitude, and the composition and lofting height of injected stratospheric mass. Since global volcanic activity is well mapped and monitored in real time from ground and space, we have a solid deterministic framework to build on that can be used to update our forecasts continuously. Low-latitude volcanoes that have longer, global impacts while higher latitude volcanoes (e.g., Iceland) have larger, shorter-term impacts in the Arctic; exploring the two types would provide broader insight into the climate-relevant coupling mechanisms. The volcanic eruption size probability function as a function of geology will be constructed by training neural networks on the wealth of archived eruption data. Variables such as magmatic activity, local geology, ground motion and gas sputtering that are used to predict volcanoes in the short term will be used as explanatory variables. This short term deterministic framework will then be scaled to decadal scale eruption forecasting and stratospheric mass injection. We will develop a reliable spatiotemporally resolved global volcanic stratospheric mass source function for use in future IPCC climate assessments. Shorter-term forecasts will be updated using real-time data from volcanic monitoring systems.[2]
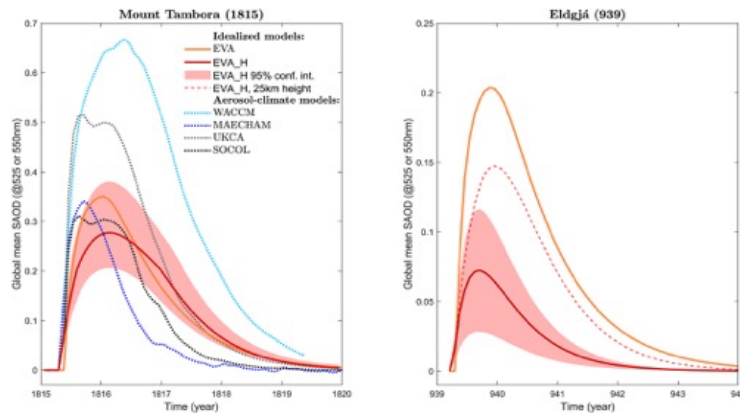
Figure 1. Global mean SAOD anomalies (left) 1815 Tambura eruption (60 Tg SO_2, 0°N, 24 km asl April); (right) 939 Eldgjá (32 Tg of SO_2, 63.6°N, 12.5 km a.s.l, April). The orange and red respectively show emulator reconstructions and shading show 95% confidence (EVA, EVA-H)/ The others are process based global models that don't agree due to different treatments.[3]

We will build on current work developing semi-empirical Stratospheric Sulfate Aerosol Forcing (SSAF) emulators, which use constraints from ice cores on the timing and mass of sulfur injected by past eruptions or scenarios of future eruptions (Fig. 1).[3] These SSAF emulators resolve the latitude, longitude, altitude, magnitude, aerosol optical depth, size-distributions, lifetime and radiative forcing of the volcanic SO_2 injections. These emulators match the 1979–1998 period characterized by the large and high-altitude tropical SO_2 injections of El Chichón (1982) and Mount Pinatubo (1991).

They also reproduce the 1998–2015 period characterized by smaller eruptions with a large variety of injection latitudes and heights. SAF emulator results compare well with the detailed reconstructions in CMIP6 for tropical high latitude warmings with extreme impacts (Tambora,1815), but high-latitude or low-altitude injections are significantly lower (Eldgja, 939). Therefore, CMIP6's last millennium experiments overestimate high-latitude volcanoes with shorter forcing periods, which impact polar regions.[3] The extinction time series from NASA's Global Space-based Stratospheric Aerosol Climatology[4] together with DOE's ARM sites (fixed and mobile) for the 1979 to 2016 period and published volcanic emissions data (date, location, mass of SO_2, and injection altitude)[5], multilinear regressions between the extinction and simple 8-box model derived time series can be used to develop and train functions via physically sound shape approximations and scaling laws. Aerosol properties such as effective particle size and optical parameters can also be approximated as a mean size and scattering with a log-normal distributions, and matched to data. A novel element of this work will be the examination of globally distributed volcanic activity, past and present, which will be used to characterize and forecast pdfs of future eruptions, particularly extreme ones. Until Pinatubo, predictions assumed the amount of volcanic gas release was governed by the volume of magma erupted and the gas saturation levels the within the magma. Pinatubo (Fig. 2) demonstrated that sulfur gas emissions were much
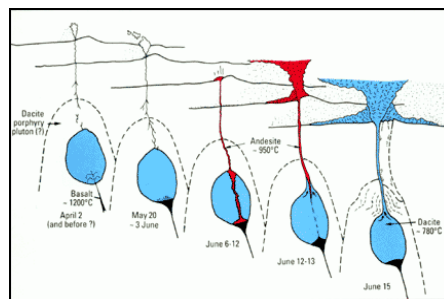
Figure 2. A picture of Pinatubo eruption (left) and model of Pinatubo's magma evolution with SO_2 gas accumulation in the magma.[1]
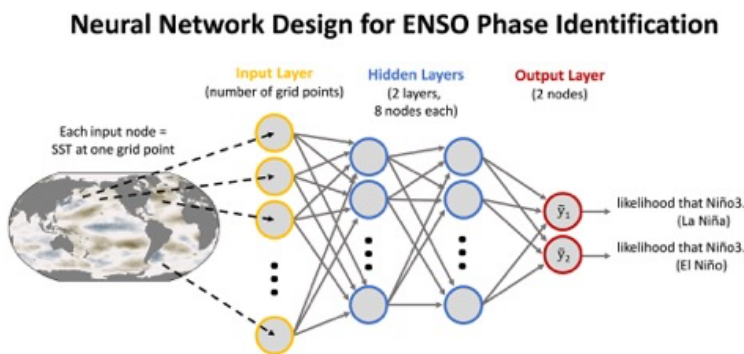
greater than expected by post-analysis of lava crystals.[1] In fact, a whopping 17 megatons of SO_2 was released, showing that that magmas can hold excess SO_2. This implied that large amounts of gas accumulate as bubbles in the magma chamber (Fig 3), which results in a huge mass lofted

high into the stratosphere. Our data driven model will incorporate this mechanism to predict extreme volcanic eruptions,[1] and application of exponentially growing data sets will provide more robust forecasts of Pinatubo-, Krakatoa- and Tambura-like events.

Elucidating Volcanic Teleconnection and Feedbacks: The extreme El Chichon and Pinatubo eruptions caused significant global cooling, drying and forest CO_2 uptake for a few years, underscoring the urgency to include them in assessments. The regional effects were more complex and much larger, including amplified, prompt Arctic cooling followed by a delayed warming due to aerosol-cloud interactions and/or interactions with natural variability.[6a,b] The framework we outline in this white paper enables a complementary focus on rapid volcanic impacts on regional temperatures, hydrology and the carbon cycle, particularly in the warming Arctic and the drying western US. While the effects are large and propagate via global teleconnections, the mechanisms are complex and not well understood. Furthermore, volcanic effects interact with natural internal modes of variability and GHG forcing via solar energy reductions and stratosphere-troposphere couplings that can amplify or damp the climate impacts on decadal timescales.

Simulations show that extreme, Tambura-like volcanoes can shift the Inter Tropical Convergence Zone (ITCZ) to promote the El Niño–Southern Oscillation (ENSO), a strong internal mode.[7] In fact, NH eruptions are shown to robustly cause El Niño-like anomalies about 6 months later, consistent with proxy-based and Pinatubo like reconstructions.[8-9] Is this coupling going to be stronger in the future as anthropogenic climate warming exceeds natural variations due to natural internal modes? Can future extreme volcanoes in a warmer world alter these internal modes and lead to abrupt large and rapid in cooling and warming as well as wetting and drying? Answers to these questions are consequential for adaptation and response, yet remain unexplored.

Figure 3. Neural network design for ENSO phase identification.[10]

We have used empirical regression analysis of climate records to disentangle the volcanic and internal mode effects, and others have used more extensive climate modeling to diagnose teleconnections from simulations.[6a,b] We propose to bridge this divide by using explainable or interpretable AI to combine statistical descriptions of past volcanic impacts with climate model simulations. Recently, neural network approaches called backward optimization and layer-wise relevance propagation, both of which project the decision pathways of a network back onto the original input dimensions, were used to elucidate atmospheric and ocean circulation changes, constructed using explainable AI on model output.[10] This AI interpretation technique has been applied successfully to interpret the El Nino phase (Fig 3), and can be used to infer meaningful trace teleconnections within the extensive climate spatiotemporal patterns following the large Pinatubo and El Chichon eruptions. In particular, we will focus on quantifying and interpreting the regional variations in the global drying after large volcanoes. Large regional drying by teleconnections and cloud feedbacks can occur in the Arctic. LANL and DOE labs house unique expertise in climate modeling, regression analysis, volcanic predictions and AI, which will all be integrated to craft a paradigm changing framework to fill this critical gap in anticipating 21st century extreme climate impacts from volcanoes.

References:

[1a] Wendel, J., and Kumar, M. (2016) Pinatubo 25 Years Later: Eight Ways the Eruption Broke Ground, AGU, EOS https://eos.org/articles/pinatubo-25-years-later-eight-ways-the-eruption-broke-ground

[1b] Haynes, P., Stratopshere-troposphere couplings, https://www.atmosp.physics.utoronto.ca/SPARC/News25/coupling.html

[2] USGS real time Volcanic hazard warning system, https://www.usgs.gov/volcano

[3] Aubry, C., T. J., Toohey, M., Marshall, L.,Schmidt, A., & Jellinek, A. M. (2020). A new volcanic stratospheric sulfateaerosol forcing emulator (EVA_H): Comparison with interactive stratospheric aerosol models, *Journal of Geophysical Research:Atmospheres*, 125, e2019JD031303.https://doi.org/10.1029/2019JD031303.

[4] Thomason, L. W., Ernest, N., Millán, L., Rieger, L., Bourassa, A., Vernier, J.-P., et al. (2018). A global space-based stratospheric aerosolclimatology: 1979–2016. *Earth System Science Data*, 10(1), 469–492

[5] Carn, S., Clarisse, L., & Prata, A. (2016). Multi-decadal satellite measurements of global volcanic degassing. *Journal of Volcanology and Geothermal Research*, 311, 99–134

[6a] Chylek, P, Folland, C., Klett, Dubey, M., CMIP5 Climate Models Overestimate Cooling by Volcanic Aerosols (2019) *Geophysical Research Letters*, https://doi.org/10.1029/2020GL087047

[6b] Dubey, M. et al. (2020) Evaluating Aerosol Solar Reflection Climate Models by Post Stratospheric Mass Injection Response Observations, GC037-0005, AGU Fall meeting, https://agu.confex.com/agu/fm20/meetingapp.cgi/Paper/706063

[7] Pausata, F. S. R. , Zanchettin, D., Karamperidou, C., Caballero, R. & Battisti, D. (2020) ITCZ shift and extratropical teleconnections drive ENSO response to volcanic eruptions. *Sci. Adv. 6*, eaaz5006.

[8] Predybaylo, E., G. L. Stenchikov, A. T. Wittenberg, and F. Zeng (2017), Impacts of a Pinatubo-Size Volcanic Eruption on ENSO, *J. Geophys. Res. Atmos*., 122, 925–947, doi:10.1002/2016JD025796.

[9] Predybaylo, E., Stenchikov, G., Wittenberg, A.T. et al. (2020) El Niño/Southern Oscillation response to low-latitude volcanic eruptions depends on ocean pre-conditions and eruption timing. *Commun Earth Environ* 1, 12. https://doi.org/10.1038/s43247-020-0013-y

[10] Toms, B. A., Barnes, E. A., & Ebert-Uphoff, I. (2020). Physically interpretable neural networks for the geosciences: Applications to Earth system variability. *Journal of Advances in Modeling Earth Systems*,12, e2019MS002002. https://doi.org/10.1029/2019MS002002